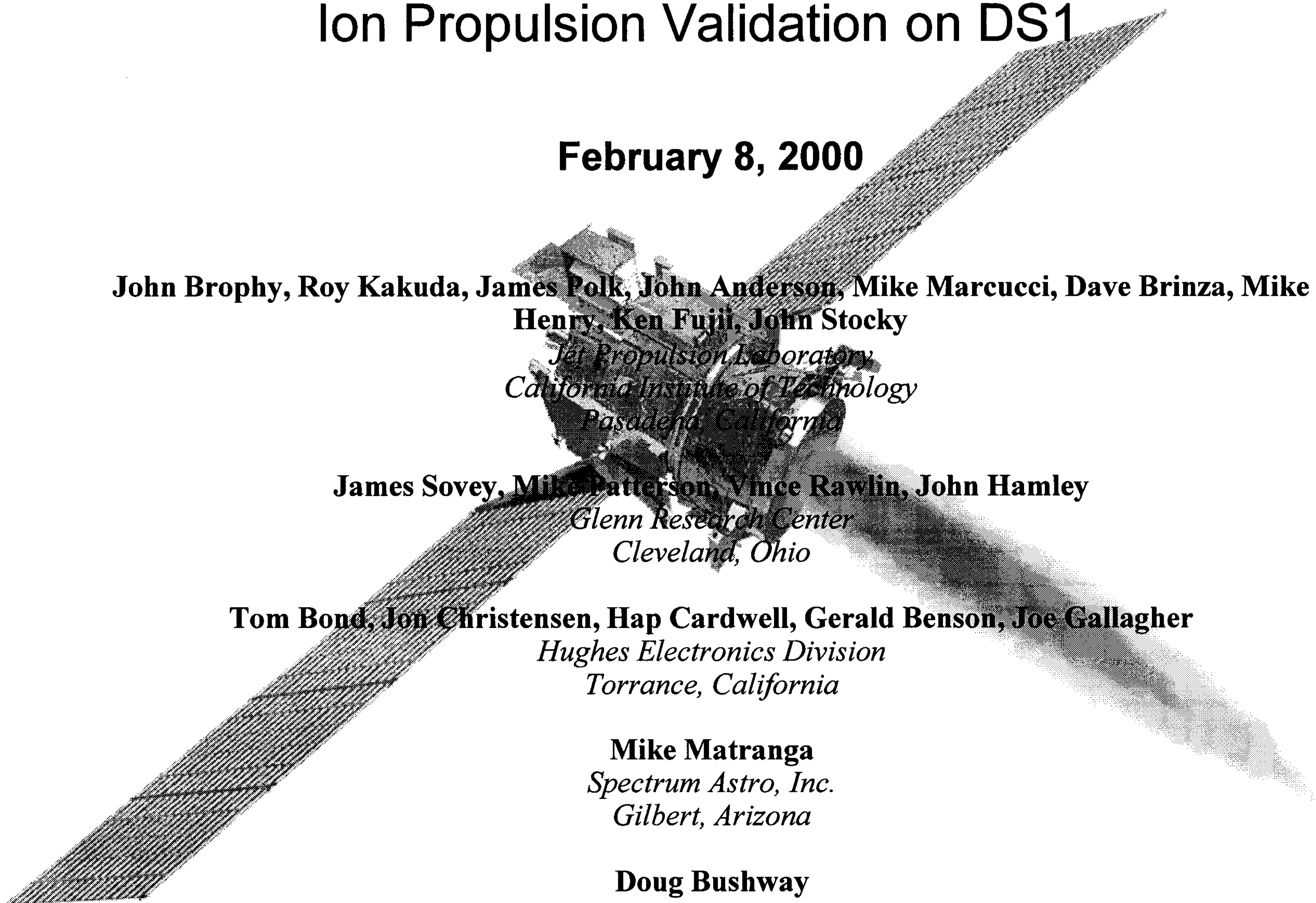
NSTAR

Ion Propulsion Validation on DS1



February 8, 2000

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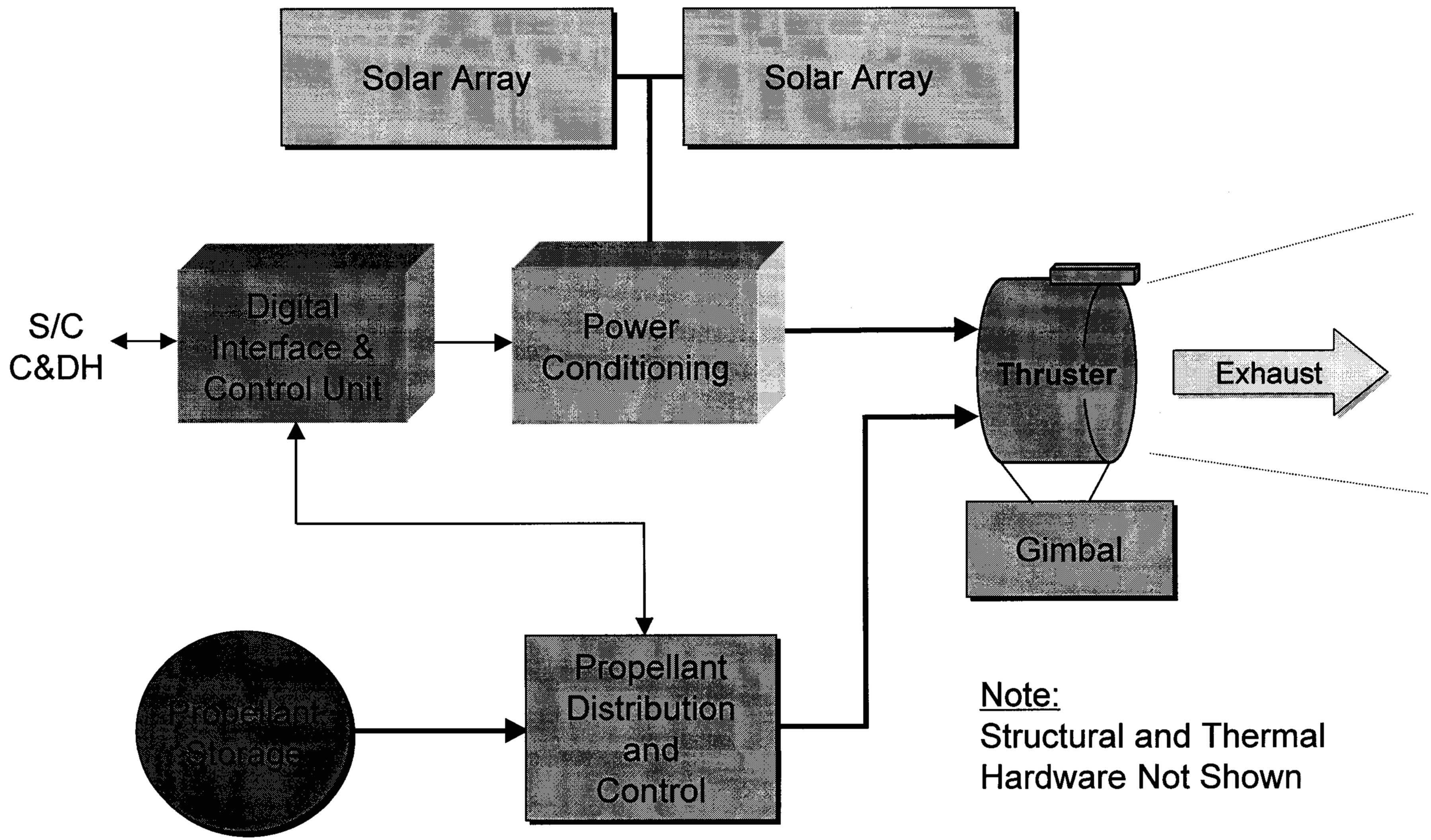
NSTAR Technology Validation Goals

1. Demonstrate that the NSTAR 30-cm diameter ion engine had sufficient life to perform missions of near-term interest -- *No one had ever successfully operated an ion engine intended for primary propulsion for its full design life*

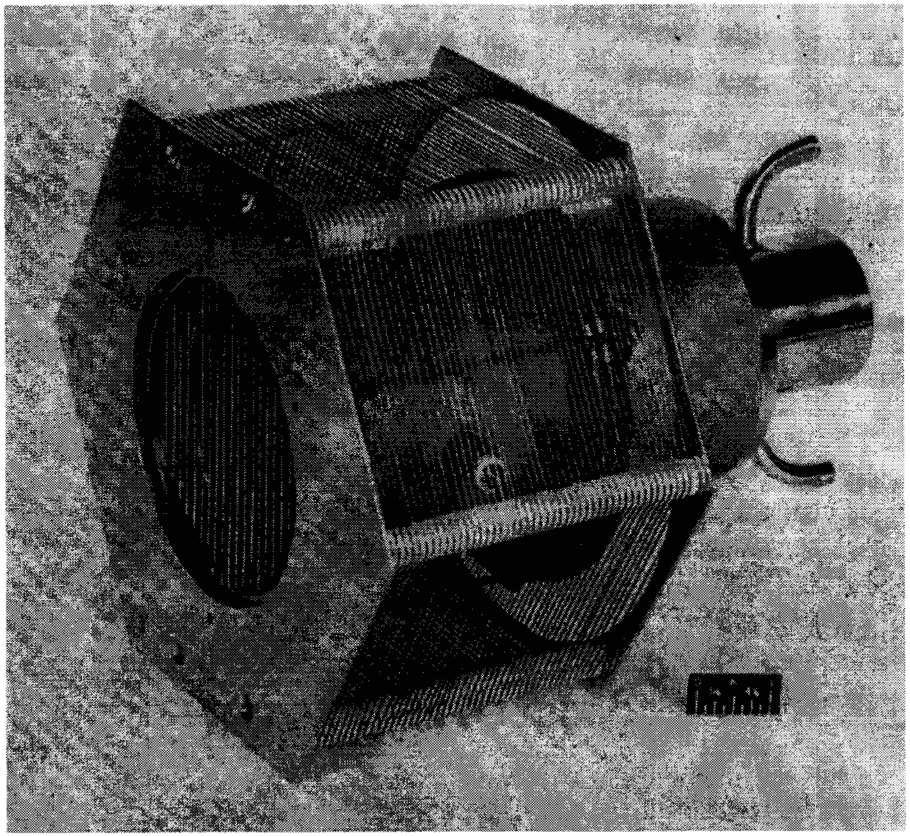
2. Demonstrate through a flight test that the ion propulsion system hardware and software could be flight qualified and successfully operated in space, and demonstrate control and navigation of an SEP spacecraft

Elements of an SEP System



Note:
Structural and Thermal
Hardware Not Shown

First Electron-Bombardment Ion Engine



- **1957:** An experimental research program in electric propulsion is initiated at Lewis Flight Laboratory

- **1959:** JPL forms a study group for electric propulsion systems

- **1959:** The first electron-bombardment ion thruster is successfully operated in the laboratory at Lewis Research Center by **Harold Kaufman**

- The performance is excellent
  - Isp = 5000s
  - efficiency > 60%

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1964 -- SERT I
Space Electric Rocket Test 1

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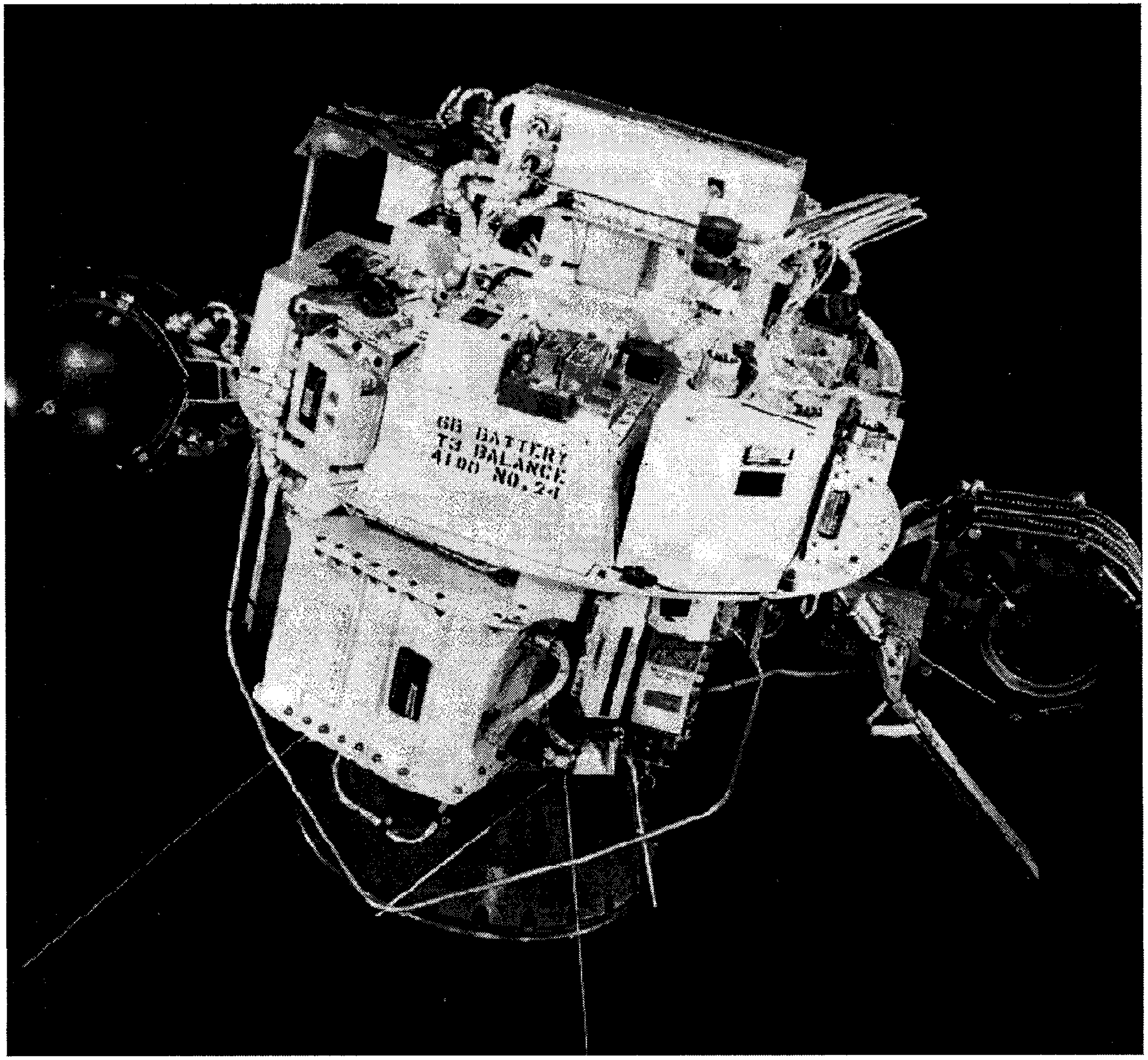
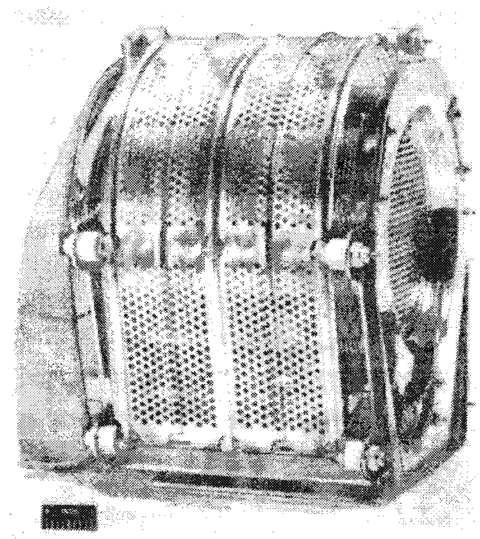


"Does she or Doesn't she?"

"She Does!"



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1970's
NASA's 30-cm Thruster

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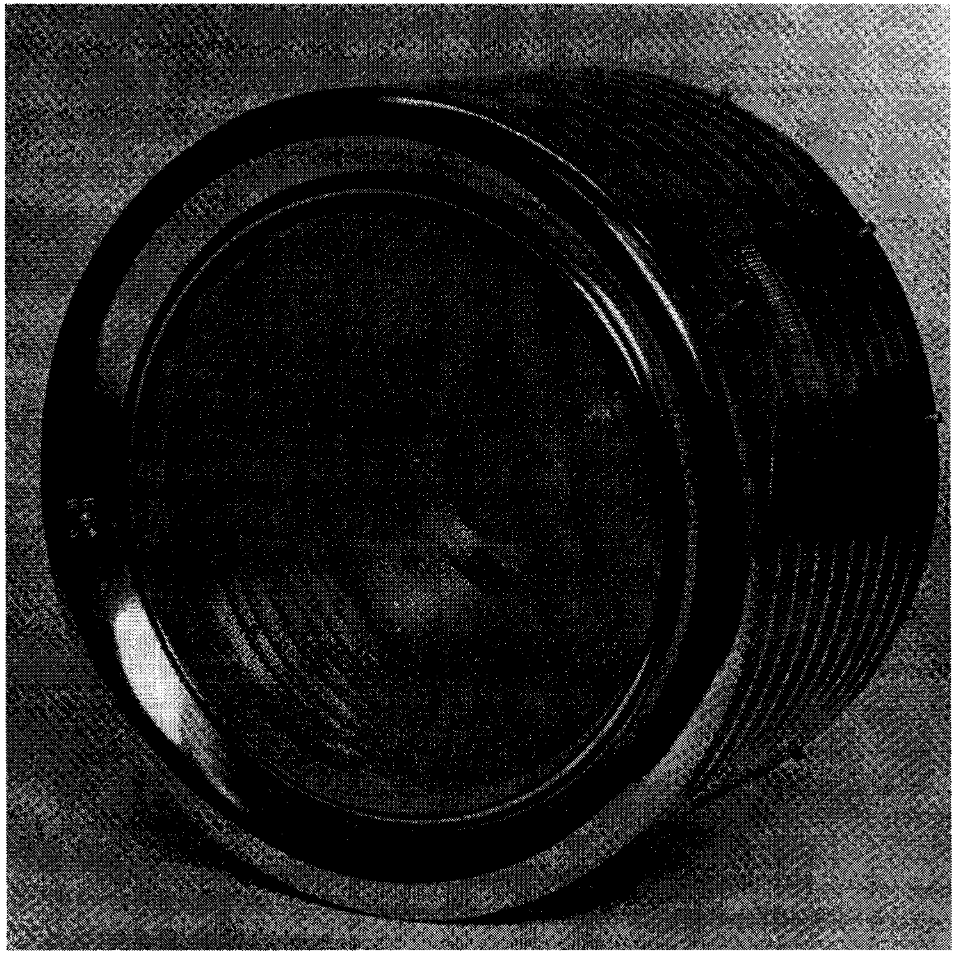

1970: Hughes-Built 30-cm Ion Engine

- **Started in 1970**
- **100 series though 900 series then J-Series (i.e., 1000 series)**
- **Major Innovation: Dished Grids (which are essentially the same as those flying on DS1**
- ***Always life test thruster with serial #1***

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NSTAR Project Schedule

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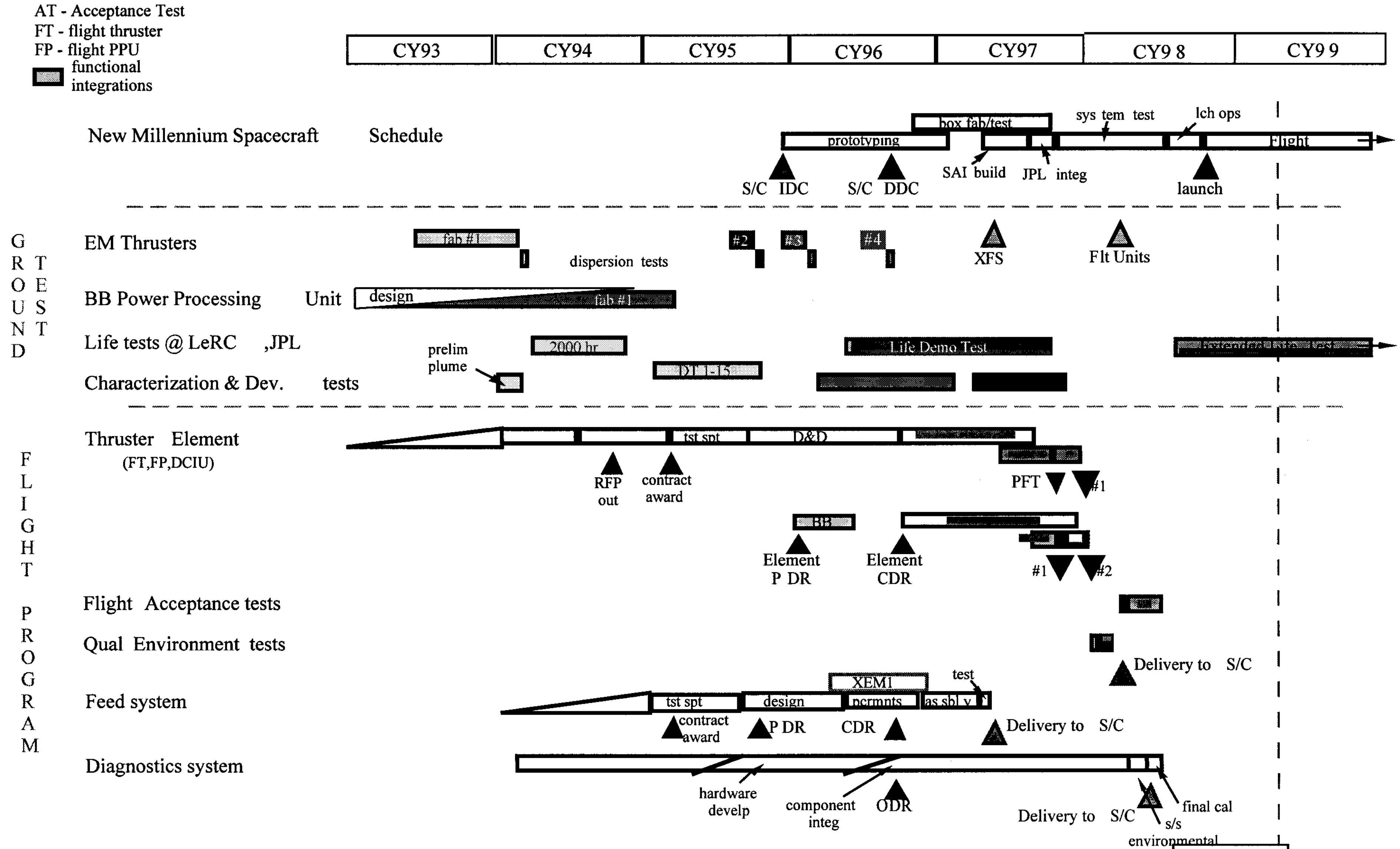

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Top 10 List of Engine Wear-Out Failure Modes

⑩ Cathode heater failure due to thermal cycling

⑨ Erosion of the neutralizer orifice plate due to plume mode operation

⑧ Structural failure of the screen grid due to ion sputtering

⑦ Structural failure of the keeper orifice plate due to ion sputtering

⑥ Structural failure of the accelerator grid or electron-backstreaming due to rogue hole formation

⑤ Unclearable short between the cathode and the keeper electrode

④ Depletion of cathode low-work-function material

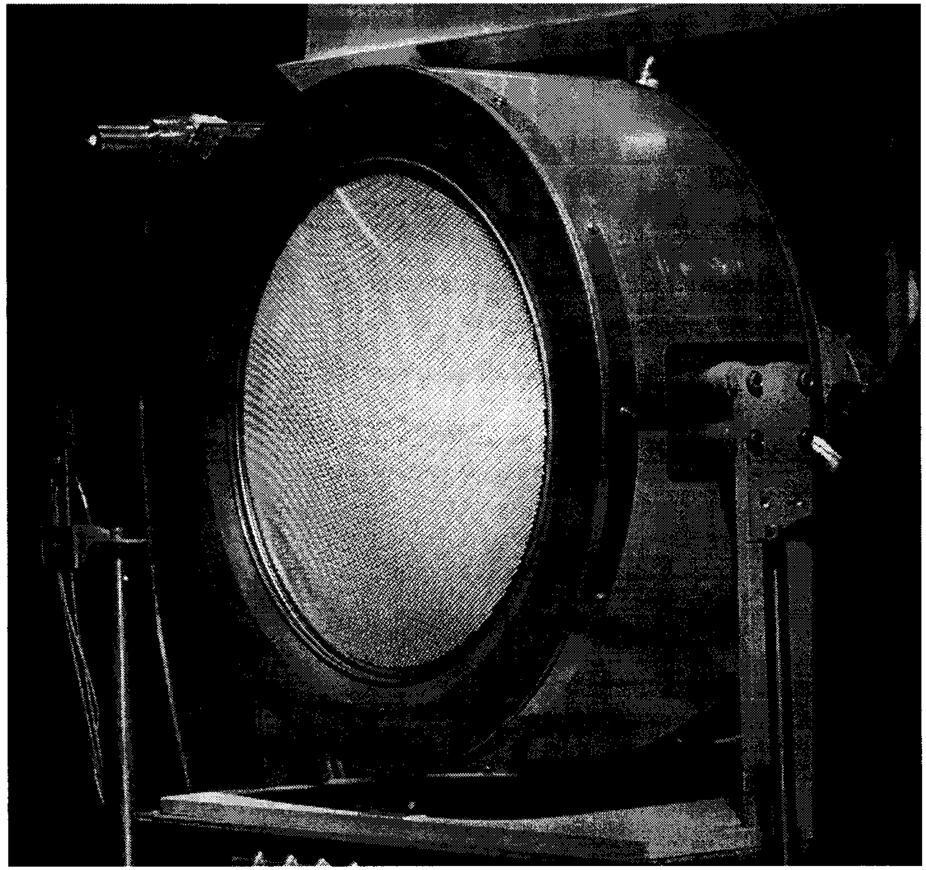
③ Unclearable short between the screen and accelerator grids

② Structural failure of the accelerator grid by charge-exchange ion erosion

① Electron-backstreaming due to enlargement of the accelerator grid apertures by ion sputtering

Engine Life Testing

- **Goals**
  - 8,000 hrs at full power with Engineering Model thruster (82 kg xenon throughput)
  - > 12,000 hrs at several thrust levels -- 125 kg xenon throughput with flight spare engine
- **Actual**
  - 8,200 hrs at full power -- 88 kg throughput demonstrated
  - 8,700 hrs with flight spare engine and counting -- 76 kg throughput demonstrated to date (as of 2/7/00)



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Cathode Erosion Solved

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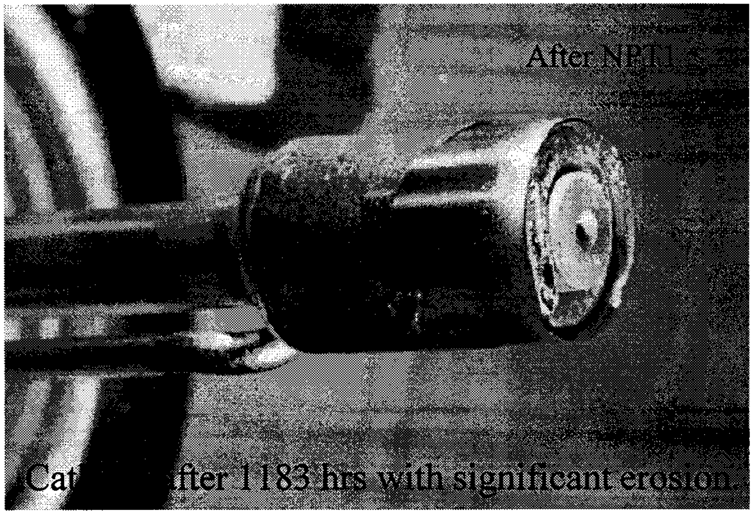
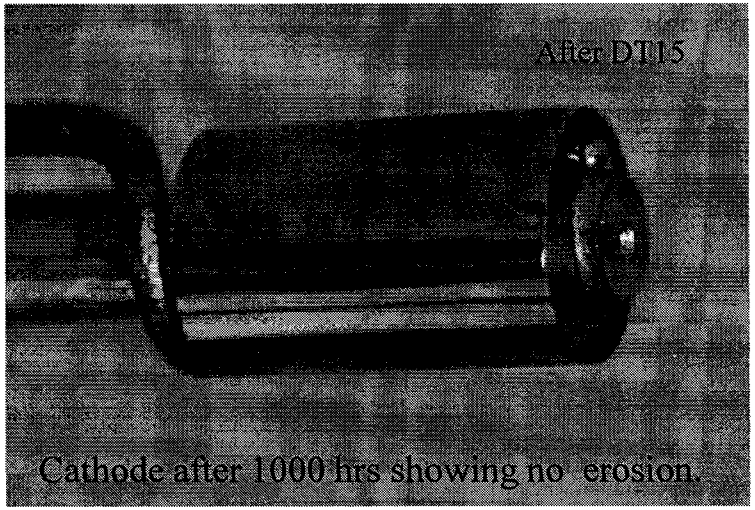
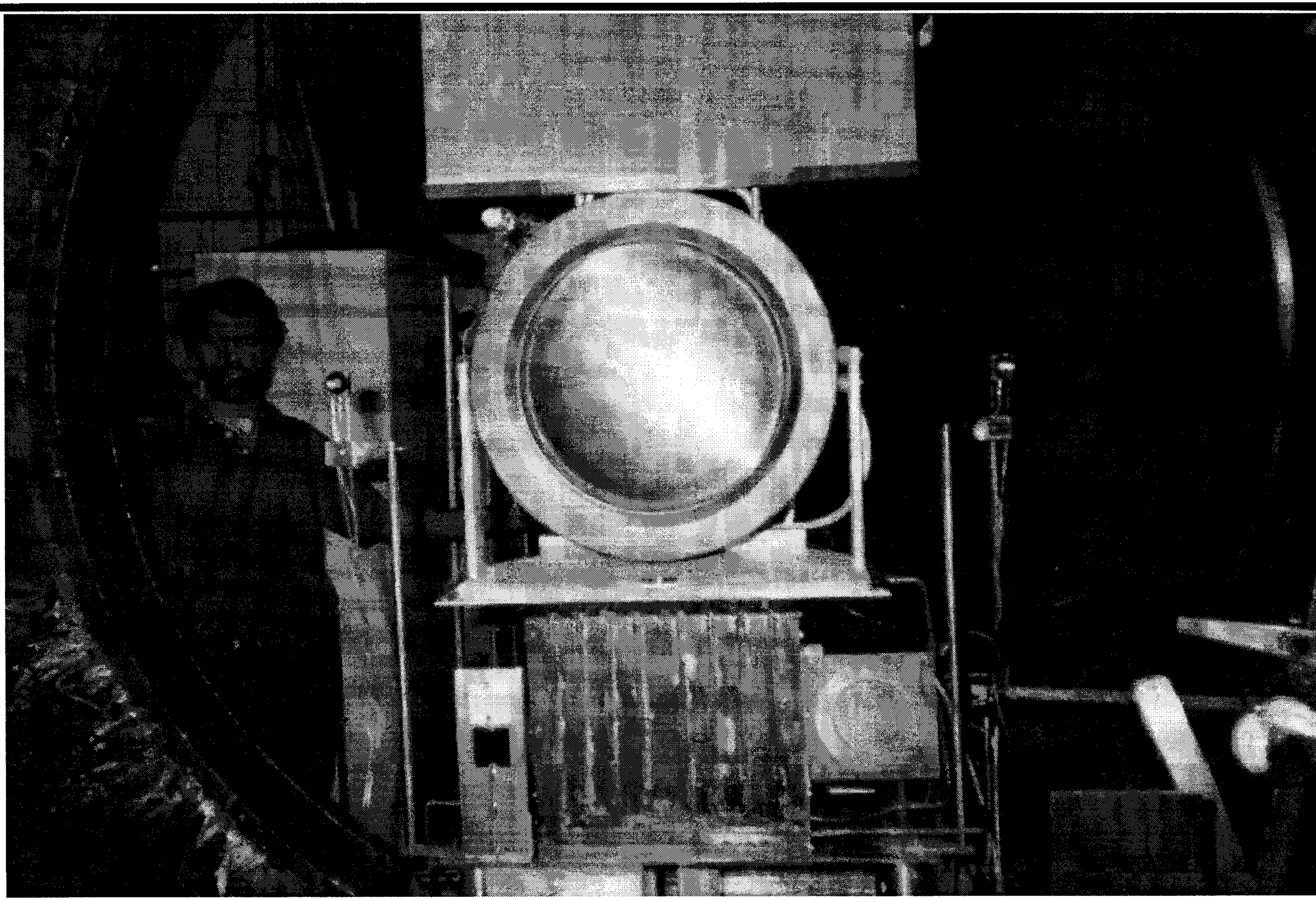
- **Significant cathode erosion observed after only 1000 hrs**

- **Used an enclosed keeper configuration to eliminate cathode erosion**





8,000-hr Life Test



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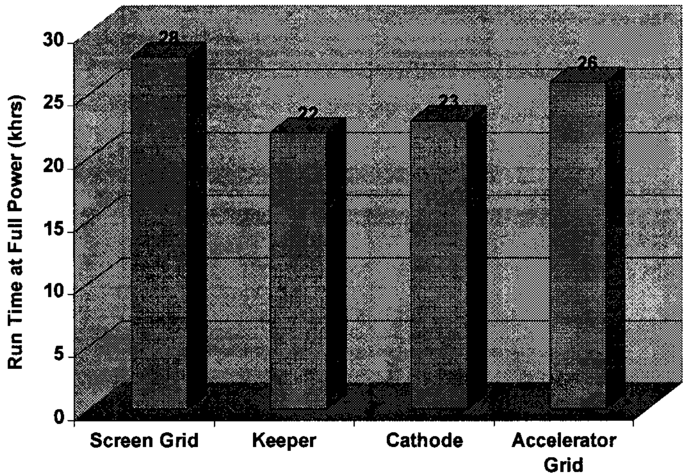
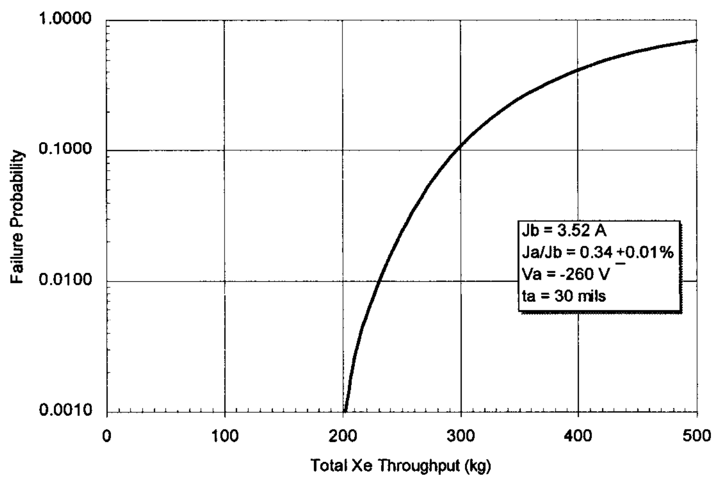
Engine Life Summary

Approximate Failure Distribution Peaks

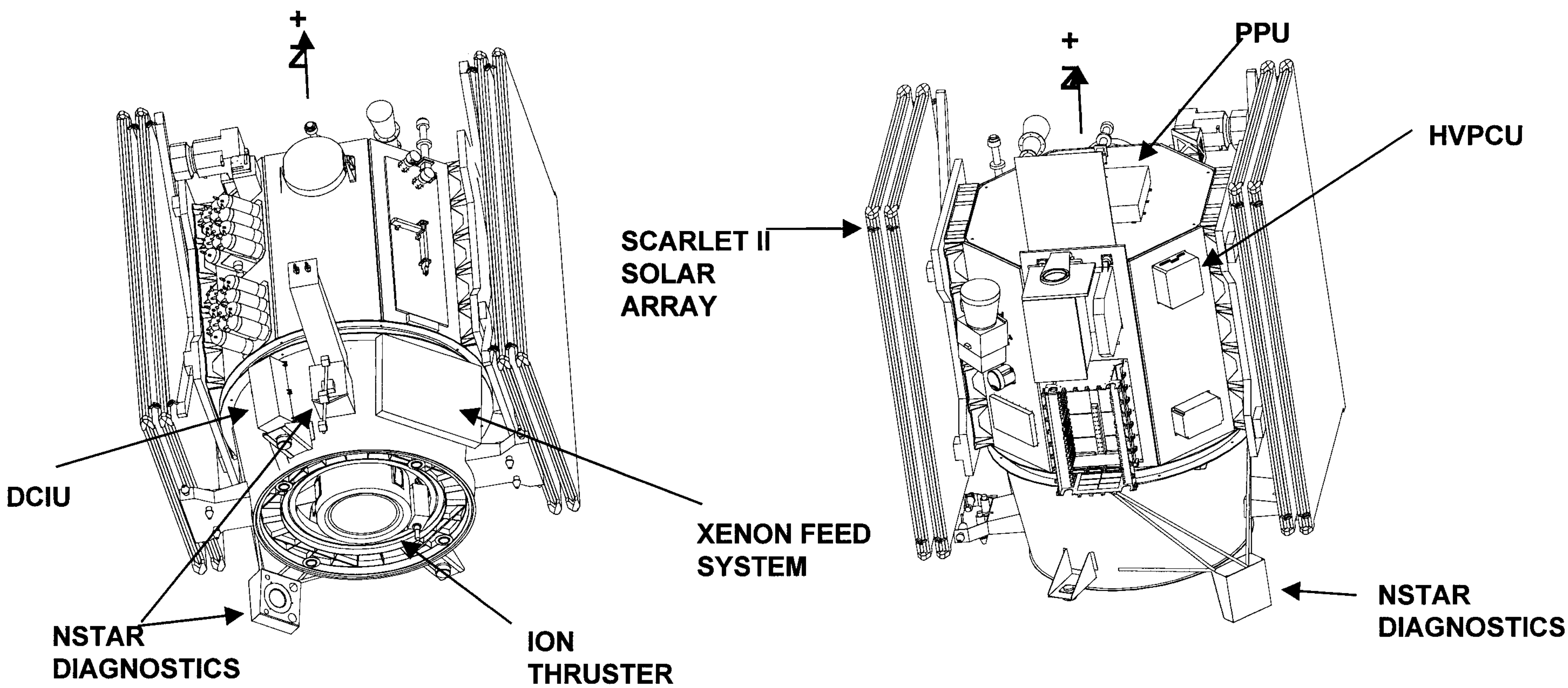




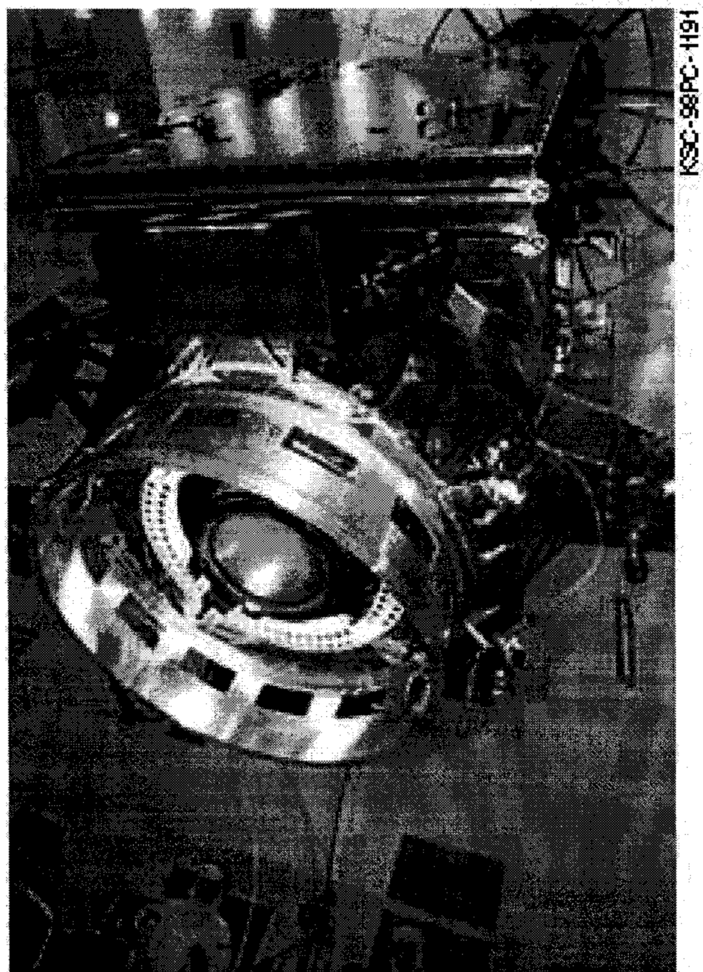
CONCLUSIONS

- **Everything in the engine will fail at the same time**
- **Performing the ST4 mission with the 3-engine system currently baselined appears to be within the engine's throughput capability**

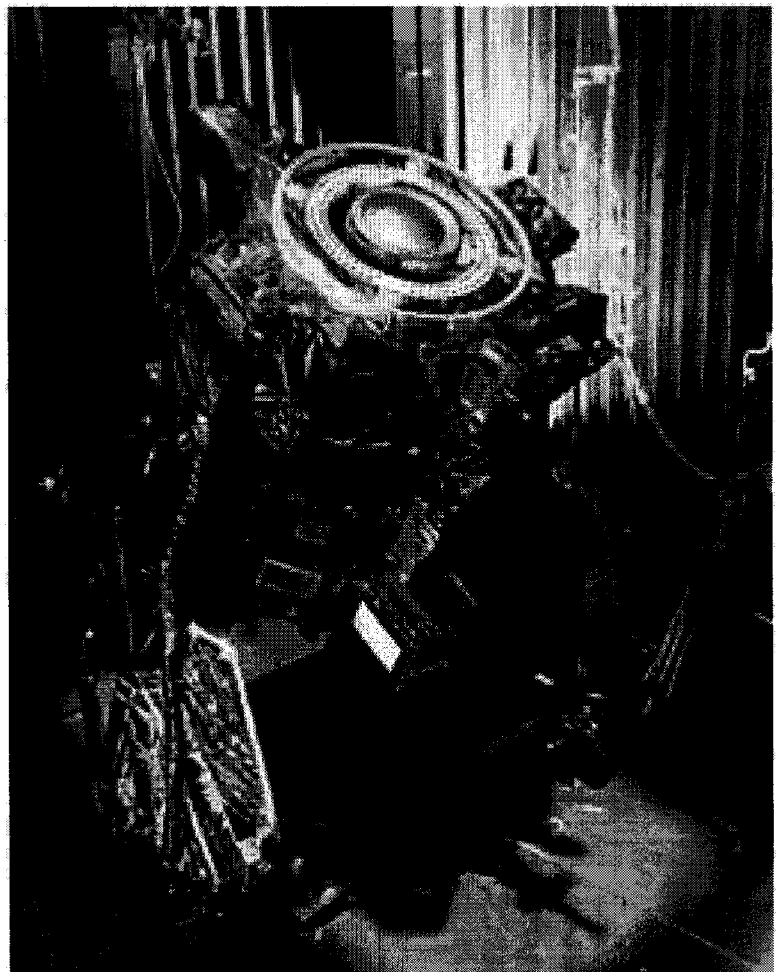
NSTAR on Deep Space 1



Deep Space 1

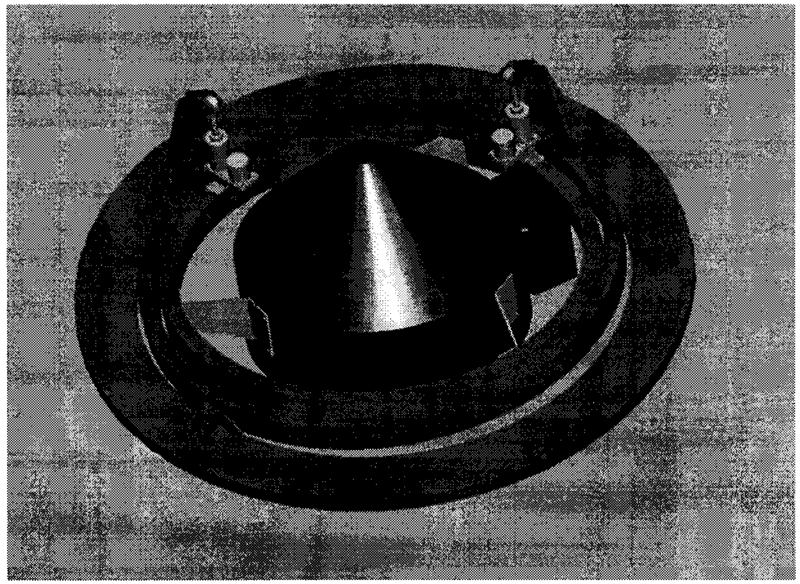


NASA/JPL/Caltech

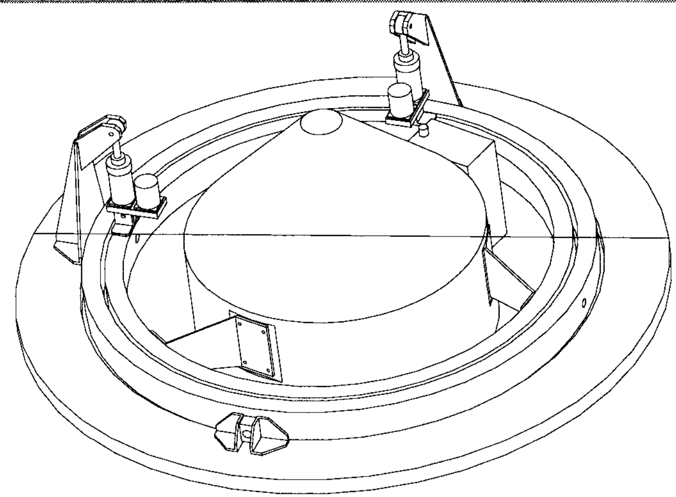


NASA/JPL/Caltech

Thruster Mounting

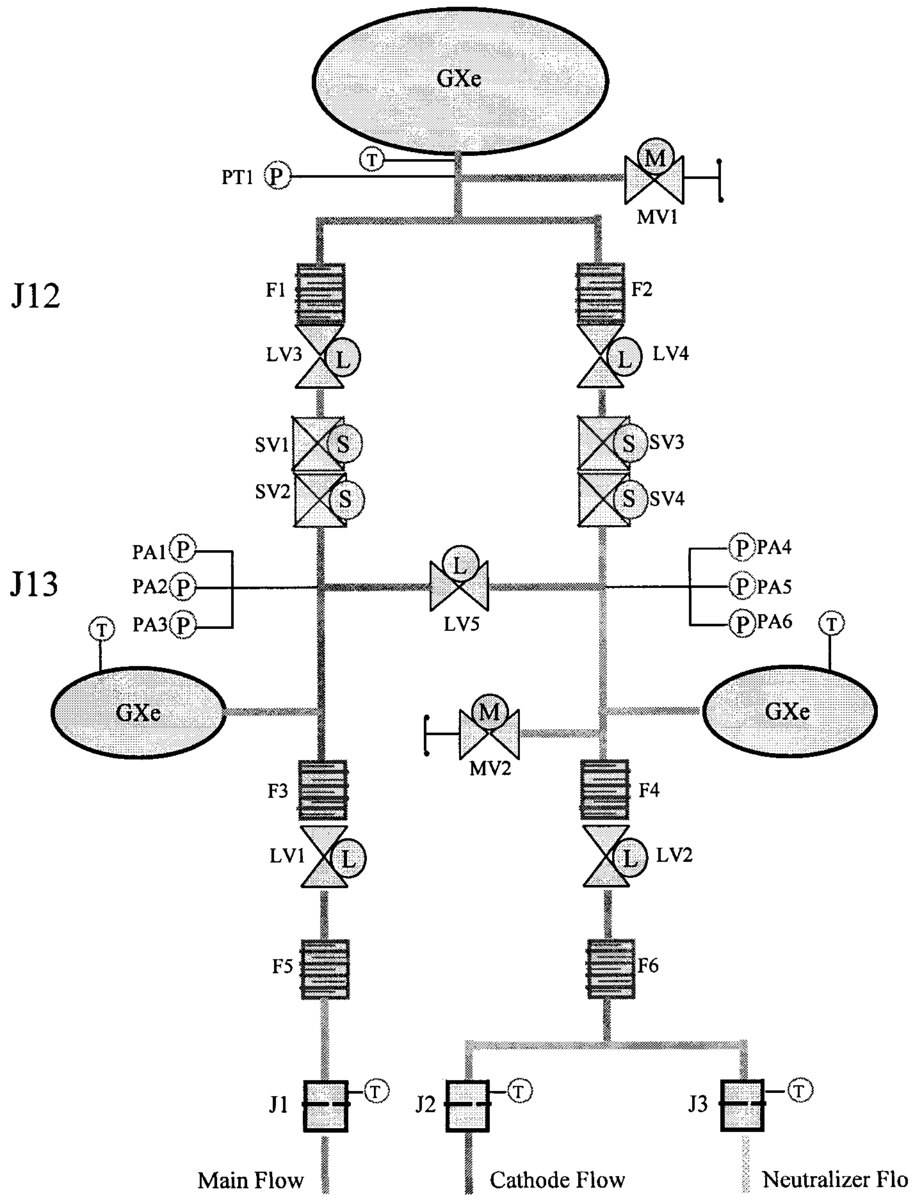


- **Two concentric mounting rings**
  - hollow aluminum channel
- **Two linear actuators**
  - enable $\pm$ 5 deg in 2 dimensions
  - 1 mrad position accuracy
- **Three flex brackets**
  - conductive isolation
  - titanium for stiffness
- **Hardware pictured - 23.26 kg**



- **Shims used to align thrust vector with C.G.**
- **Thermal cover not shown**
- **Thruster - PPU cable is ~4.8 m long**
  - minimize length if possible

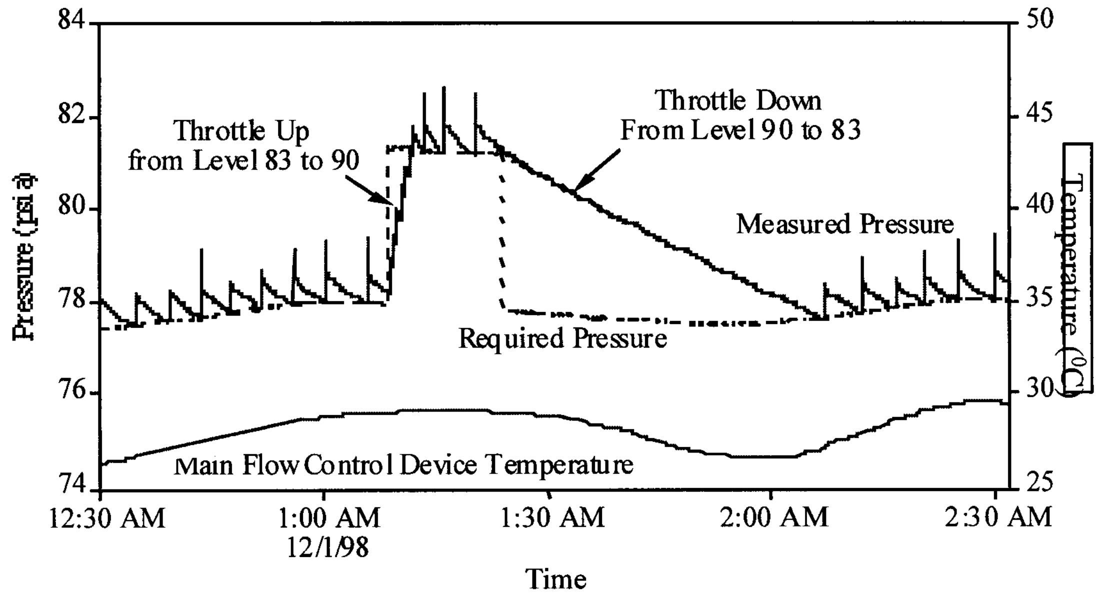
XFS


GXe
PT1
P
T
M
MV1
J12
F1
F2
LV3
L
LV4
SV1
S
SV3
SV2
SV4
J13
PA1
PA2
PA3
PA4
PA5
PA6
LV5
GXe
GXe
MV2
F3
F4
LV1
LV2
F5
F6
J1
J2
J3
Main Flow
Cathode Flow
Neutralizer Flo

In-Flight Data Results

Xenon flow:

- **Main flow behavior during power increases and decreases is shown**
  - sawtooth magnitude dependent on main tank pressure
  - new power level selected determines the negative slope
  - shows operation is slightly rich
- **Effects most pronounced during start - can take 7 hours to bleed down**
  - cathodes always start at 3.6 sccm (maximum value)
- **Voting algorithm for pressure tranducers is key to proper flow control**



- **Initial design considered 1,2,3 plenum tanks**
- **Variable set point regulator is needed**
  - ✓ NSTAR: 2-30 sccm xenon
  - ✓ low flows need to be stable

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In-Flight Data Results

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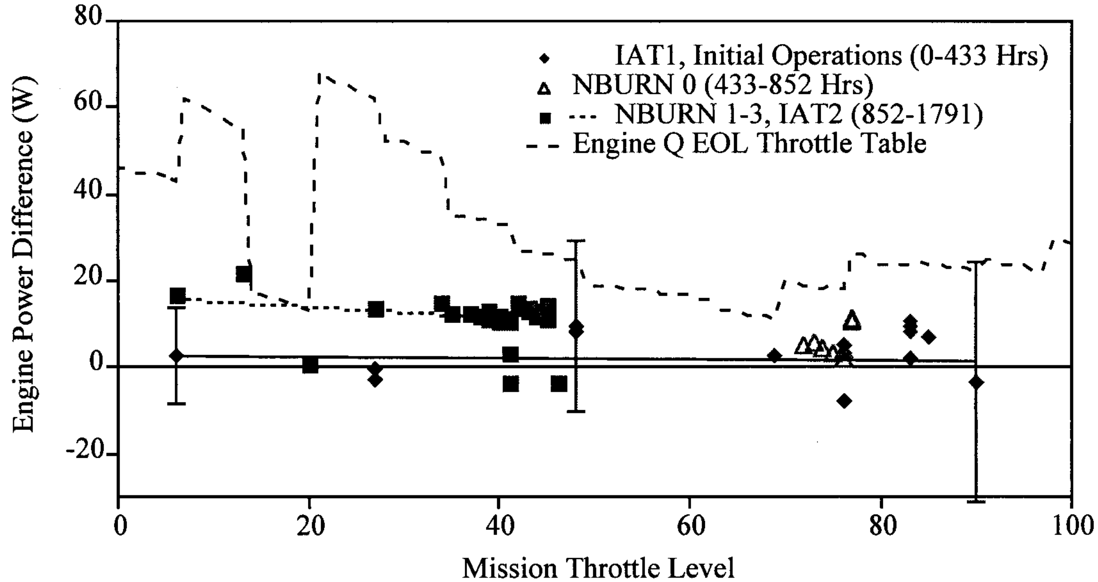
Power and Thrust:

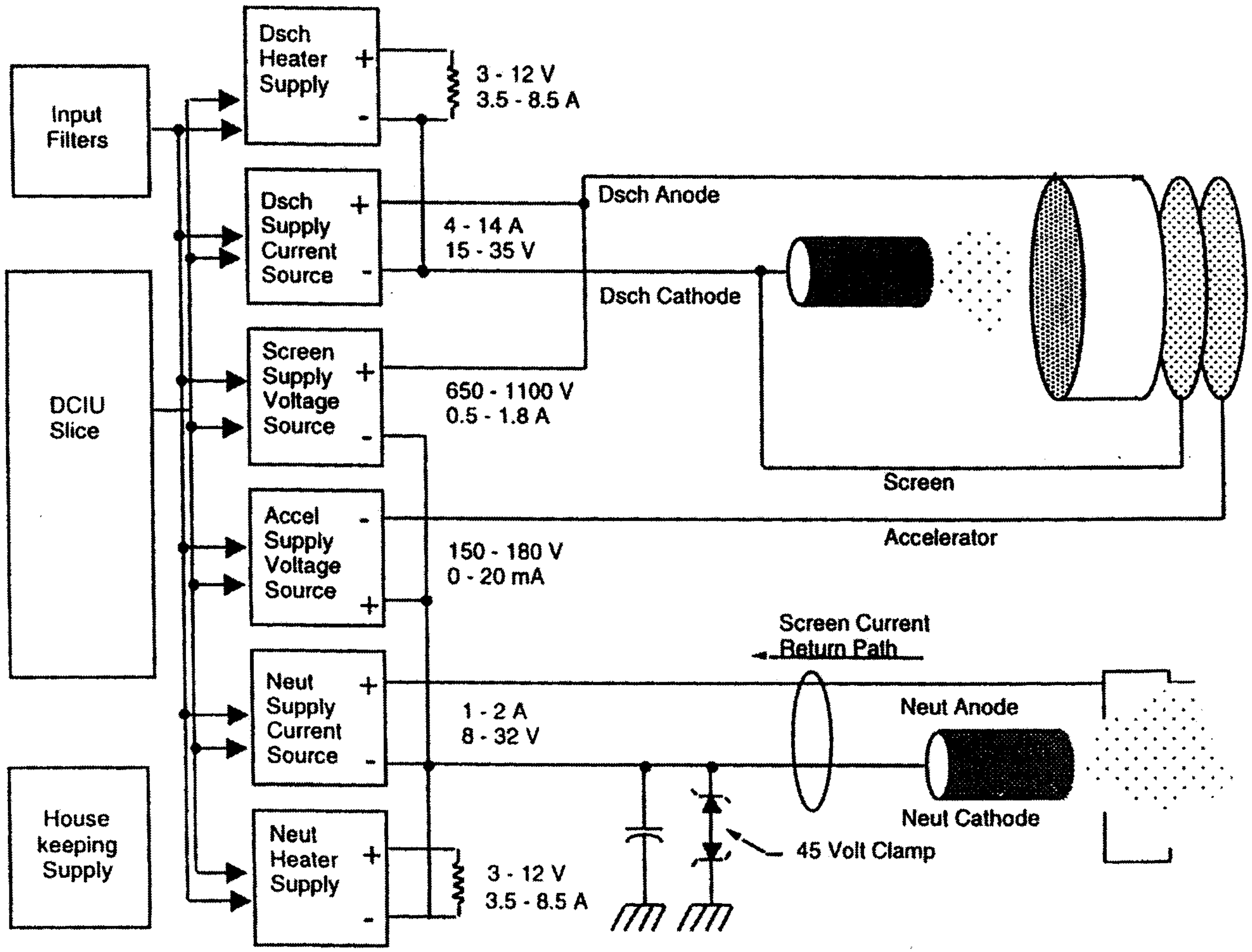
- **Doppler measurements within 0.5 mN**
  - team can identify the initiation of xenon flow before cathode start
- **$T = f(J_b, V_b, V_g, M_{xe}, e)$**
- **Expected values were from test data**



- **Ideal: symbols on 0 line**
- **Actual: ¦ initial power levels close**
  ¦ later power levels are high
- **Cannot recheck initial levels yet**

- **Today's question: does the thruster behave differently in flight, was the ground data biased low, or is differing PPU efficiency introducing the variation?**

PPU Block Diagram



Summary

- **Ground test program more extensive than the original plan**
  - 13780 total test hours on 5 EM thrusters
  - direct contributor to 7800+ flight thruster hours (increasing by -300 hrs/week)
- **EMs proved invaluable**
  - development test costs were low
  - equipment handling practices and purge procedures were documented
  - diode mode proven with no risk to flight units
  - substitutions in system test enabled schedule to be preserved
- **Hardware proved to be interchangeable**
  - telemetry calibrations virtually the same for both PPUs
  - need to be conscientious about location of sense measurements & cable lengths
- **Original Project Plan did not include an end-to-end test (to save costs)**
  - risk eventually seen as too high for the savings
- **Flight data compares reasonably with expectations**
  - no interactions with plasma or optical instruments
  - diagnostics measurements detect many spacecraft events
  - operations are now routine

Future Missions That Benefit from SEP

- CNSR
- Venus Surface Sample Return
- Europa Lander
- Titan Explorer
- Saturn Ring Observer
- Neptune Orbiter